UNITED STATES PATENT APPLICATION

FOR

METHOD AND APPARATUS FOR MODULATING AN OPTICAL BEAM IN AN OPTICAL DEVICE WITH A PHOTONIC CRYSTAL LATTICE

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BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates generally to optics and, more specifically, the present invention relates to modulating optical beams.

Background Information

The need for fast and efficient optical-based technologies is increasing as Internet data traffic growth rate is overtaking voice traffic pushing the need for optical communications. Transmission of multiple optical channels over the same fiber in the dense wavelength-division multiplexing (DWDM) systems and Gigabit (GB) Ethernet systems provide a simple way to use the unprecedented capacity (signal bandwidth) offered by fiber optics. Commonly used optical components in the system include wavelength division multiplexed (WDM) transmitters and receivers, optical filter such as diffraction gratings, thin-film filters, fiber Bragg gratings, arrayed-waveguide gratings, optical add/drop multiplexers, lasers and optical switches. Optical switches may be used to modulate optical beams. Two commonly found types of optical switches are mechanical switching devices and electro-optic switching devices.

Mechanical switching devices generally involve physical components that are placed in the optical paths between optical fibers. These components are moved to cause switching action. Micro-electronic

mechanical systems (MEMS) have recently been used for miniature mechanical switches. MEMS are popular because they are silicon based and are processed using somewhat conventional silicon processing technologies. However, since MEMS technology generally relies upon the actual mechanical movement of physical parts or components, MEMS are generally limited to slower speed optical applications, such as for example applications having response times on the order of milliseconds.

In electro-optic switching devices, voltages are applied to selected parts of a device to create electric fields within the device. The electric fields change the optical properties of selected materials within the device and the electro-optic effect results in switching action. Electro-optic devices typically utilize electro-optical materials that combine optical transparency with voltage-variable optical behavior. One typical type of single crystal electro-optical material used in electro-optic switching devices is lithium niobate ($LiNbO_3$).

Lithium niobate is a transparent material from ultraviolet to mid-infrared frequency range that exhibits electro-optic properties such as the Pockels effect. The Pockels effect is the optical phenomenon in which the refractive index of a medium, such as lithium niobate, varies with an applied electric field. The varied refractive index of the lithium niobate may be used to provide switching. The applied electrical field is provided to present day electro-optical switches by external control circuitry.

Although the switching speeds of these types of devices are very fast, for example on the order of nanoseconds, one disadvantage with present day electro-optic switching devices is that these devices generally require relatively high voltages in order to switch optical beams. Consequently, the external circuits utilized to control present day electro-optical switches are usually specially fabricated to generate the high voltages and suffer from large amounts of power consumption. In addition, integration of these external high voltage control circuits with present day electro-optical switches is becoming an increasingly challenging task as device dimensions continue to scale down and circuit densities continue to increase.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention is illustrated by way of example and not limitation in the accompanying figures.

Figure 1 is a diagram illustrating generally one embodiment of an optical device including a photonic crystal lattice in semiconductor having a waveguide through which an optical beam is directed and modulated in accordance with the teachings of the present invention.

Figure 2A is a plan view diagram illustrating generally holes etched into an epitaxial layer a silicon-on-insulator (SOI) wafer according to one embodiment of an optical device in accordance with the teachings of the present invention.

Figure 2B is a cross section diagram illustrating generally holes etched into the epitaxial layer of the SOI wafer according to one embodiment of an optical device in accordance with the teachings of the present invention.

Figure 3A is a plan view diagram illustrating generally an insulating region formed over the holes that were etched into the epitaxial layer of the SOI wafer according to one embodiment of an optical device in accordance with the teachings of the present invention.

Figure 3B is a cross section diagram illustrating generally the insulating region formed over the holes that were etched into the epitaxial layer of the SOI wafer according to one embodiment of an optical device in accordance with the teachings of the present invention.

Figure 4A is a plan view diagram illustrating generally second semiconductor regions formed over the insulating regions that were formed over the holes that were etched into the epitaxial layer of the SOI wafer according to one embodiment of an optical device in accordance with the teachings of the present invention.

Figure 4B is a cross section diagram illustrating generally second semiconductor regions formed over the insulating regions that were formed over the holes that were etched into the epitaxial layer of the SOI wafer according to one embodiment of an optical device in accordance with the teachings of the present invention.

Figure 5A is a plan view diagram illustrating generally contacts to the epitaxial layer of the SOI wafer and an optical beam directed through a resulting optical waveguide through the photonic crystal lattice in the epitaxial layer of the SOI wafer according to one embodiment of an optical device in accordance with the teachings of the present invention.

Figure 5B is a cross section diagram illustrating generally contacts to the epitaxial layer of the SOI wafer and an optical beam directed through a resulting optical waveguide through the photonic crystal lattice in the epitaxial layer of the SOI wafer according to one embodiment of an optical device in accordance with the teachings of the present invention.

Figure 6A is a diagram illustrating generally a voltage signal applied to a photonic crystal lattice according to one embodiment of the present

invention to modulate charge in charge modulated regions in accordance with the teachings of the present invention.

Figure 6B is a diagram illustrating generally a current signal injected into a photonic crystal lattice according to one embodiment of the present invention to modulate charge in charge modulated regions in accordance with the teachings of the present invention.

Figure 6C is a diagram illustrating generally in greater detail charges in a charge modulated region in accordance with the teachings of the present invention.

Figure 7A is a diagram illustrating generally an optical beam having a plurality of wavelengths directed through an optical waveguide through a photonic crystal lattice with a "low" voltage signal applied in accordance with the teachings of the present invention.

Figure 7B is a diagram illustrating generally an optical beam having a plurality of wavelengths directed through an optical waveguide through a photonic crystal lattice with a "high" voltage signal applied in accordance with the teachings of the present invention.

Figure 8 is a diagram illustrating one embodiment of a system including an optical transmitter, an optical receiver and an optical device including a photonic crystal lattice to modulate an optical beam in accordance with the teachings of the present invention.

DETAILED DESCRIPTION

Methods and apparatuses for modulating an optical beam with an optical device having a photonic crystal lattice are disclosed. In the following description numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be apparent, however, to one having ordinary skill in the art that the specific detail need not be employed to practice the present invention. In other instances, well-known materials or methods have not been described in detail in order to avoid obscuring the present invention.

Reference throughout this specification to "one embodiment" or "an embodiment" means that a particular feature, structure or characteristic described in connection with the embodiment is included in at least one embodiment of the present invention. Thus, appearances of the phrases "in one embodiment" or "in an embodiment" in various places throughout this specification are not necessarily all referring to the same embodiment. Furthermore, the particular features, structures or characteristics may be combined in any suitable manner in one or more embodiments. In addition, it is appreciated that the figures provided herewith are for explanation purposes to persons ordinarily skilled in the art and that the drawings are not necessarily drawn to scale.

In one embodiment of the present invention, a semiconductor-based optical device is provided in a fully integrated solution on a single integrated circuit chip. One embodiment of the presently described optical device

includes a semiconductor-based photonic crystal lattice patterned in semiconductor material through which an optical waveguide is directed. The optical device exploits the photonic band gap in the photonic crystals of the photonic crystal lattice. The photonic band gap of the photonic crystal lattice will block a wavelength of an optical beam while allowing other wavelengths of the optical beam to propagate.

As will be discussed, in order for a particular wavelength to experience the photonic band gap, a photonic crystal lattice according to embodiments of the present invention has a particular hole radius, a particular hole pitch and is made of a material having a particular index of refraction. In one embodiment, the effective hole radius of the holes of the photonic crystal lattice is modulated by modulating the index of refraction of the material defining or surrounding the holes of the photonic crystal lattice. In one embodiment, the index of refraction of the material defining the holes is modulated by modulating charge in charge modulated regions that are proximate to the holes of the photonic crystal lattice in accordance with the teachings of the present invention. Embodiments of the disclosed optical devices can be used in a variety of high bandwidth applications including multi-processor, telecommunications, networking as well as other high speed optical applications such as optical switches, modulators, or the like.

To illustrate, Figure 1 is a diagram illustrating generally one embodiment of an optical device including a photonic crystal lattice

fabricated in semiconductor material and having photonic band gap that can be modulated in accordance with the teachings of the present invention. As shown in Figure 1, optical device 101 includes semiconductor material 103 in which a photonic crystal lattice 105 is disposed. In one embodiment, an optical waveguide is included in semiconductor material 103 and is directed through photonic crystal lattice 105 as shown in Figure 1. A plurality of holes 107 are periodically arranged in semiconductor material 103 having a hole pitch and a hole radius that define photonic crystal lattice 105 in semiconductor material 103. In one embodiment, the hole pitch is approximately 500 nanometers and the hole radius is approximately 200 nanometers. It is appreciated of course that other hole pitch and hole radius dimensions may be utilized in other embodiments in accordance with the teachings of the present invention. The resulting photonic band gap of photonic crystal lattice 105 is determined by the hole pitch and the hole radius of the photonic crystal lattice 105.

An optical beam 111 having at least one wavelength is directed through optical waveguide 109 through semiconductor material 103 and photonic lattice 105. The photonic band gap of photonic crystal lattice 105 gives rise to a range of frequencies or wavelengths of optical beam 111 that cannot propagate through photonic crystal lattice 105. As a result, if a particular wavelength of optical beam 111 corresponds to the photonic band gap of photonic crystal lattice 105, then that particular wavelength of optical beam 111 is blocked while other wavelengths, if any, included in optical

beam 111 are allowed to propagate freely through photonic crystal lattice 105.

As will be discussed, in one embodiment, charge modulated regions proximate to the plurality of holes are included in optical device 101 in accordance with the teachings of the present invention. In operation, a signal 113 is applied to photonic crystal lattice 105. In one embodiment, signal 113 may be a voltage signal while in another embodiment, signal 103 may be a current signal in accordance with the teachings of the present invention. The concentration of free charge carriers in the charge modulated regions is modulated in response to signal 113. As a result of this charge modulation, the index of refraction of the semiconductor material proximate to the plurality of holes 107 is modulated. As a result of this modulated index of refraction of the semiconductor material proximate to the plurality of holes 107, the effective hole diameter of the plurality of holes is modulated. As a result of this modulated hole diameter of the plurality of holes 107, the effective photonic band gap of photonic crystal lattice 105 is modulated. Therefore, optical beam 111, which includes the particular wavelength corresponding to the photonic band gap of photonic crystal lattice 105, is modulated in accordance with the teachings of the present invention.

In one embodiment, semiconductor material 103 is the epitaxial layer of a silicon-on-insulator (SOI) wafer. To illustrate, Figure 2A is a plan view diagram of semiconductor material 103 of the epitaxial layer of an SOI wafer

illustrating generally the plurality of holes 107 of photonic crystal lattice 105 are etched in semiconductor material 103 in accordance with the teachings of the present invention. In addition, Figure 2B is a cross section diagram illustrating generally the plurality of holes 107 etched into the semiconductor material 103 of the epitaxial layer of the SOI wafer in accordance with the teachings of the present invention. In one embodiment, semiconductor material 103 has a particular index of refraction and the plurality of holes 107 are arranged in semiconductor material 103 with a hole pitch and hole that define photonic crystal lattice 105 with a particular band gap. As shown in Figures 2A and 2B, the SOI wafer includes a buried insulating region disposed between the semiconductor material 103 of the epitaxial layer and a buried semiconductor layer 215. In one embodiment, the plurality of holes 107 are etched in semiconductor material 103 down to the buried insulating layer 213. It is noted that in another embodiment, the plurality of holes 107 may be etched only partially through semiconductor material 103 and not down to buried insulating layer 213.

After the plurality of holes 107 are etched into the semiconductor material 103 of the epitaxial layer of an SOI wafer as shown in Figures 2A and 2B, Figure 3A shows a plan view diagram illustrating generally an insulating region 317 that is then formed over semiconductor material 103 including inside surfaces of the plurality of holes 107 of photonic crystal lattice 105 according to one embodiment of the present invention. Figure

3B is a cross section diagram illustrating generally the insulating region 317 formed over the plurality of holes 107 according to one embodiment of the present invention. In one embodiment, insulating region 317 includes oxide and is formed with a thickness of approximately 120 Angstroms. It is appreciated of course that other insulating materials and other thicknesses may be utilized in other embodiments in accordance with the teachings of the present invention.

After the insulating region 317 is formed over semiconductor material 103 as shown in Figures 3A and 3B, Figure 4A shows a plan view diagram illustrating generally second semiconductor material regions 419 formed over the insulating region 317 according to an embodiment of the present invention. Figure 4B is a cross section diagram illustrating generally second semiconductor material regions 419 formed over the insulating region 317 according to an embodiment of the present invention. As shown in the embodiment depicted in Figures 4A and 4B, second semiconductor regions 419 are patterned over insulating region 317 including regions proximate to the inside surfaces of the plurality of holes 107 of photonic crystal lattice 105. The embodiment illustrated in Figure 4A shows that second semiconductor material regions 419 are patterned such that each of the second semiconductor material regions 419 are coupled together. In one embodiment, contacts such as for example contacts 421 and 423 are included to provide electrical access to the second semiconductor material regions 419 that are proximate to the inside surfaces of the plurality of

holes 107 of photonic crystal lattice 105. With insulating region 317, it is appreciated that second semiconductor material regions 419 are electrically insulated from semiconductor material 103 in accordance with the teachings of the present invention. It is appreciated therefore that a capacitive structures result from semiconductor material 103 being insulated from second semiconductor material regions 419 with insulating region 317 in accordance with the teachings of the present invention.

After the second semiconductor material regions 419 formed over the insulating region 317 as shown in Figures 4A and 4B, Figure 5A shows a plan view diagram illustrating generally contacts 525 and 527 formed to provide electrical couplings to semiconductor material 103 according to an embodiment of the present invention. Figure 5B is a cross section diagram illustrating generally contacts formed to provide electrical couplings to semiconductor material 103 according to an embodiment of the present invention. In an embodiment in which an electrical coupling is not necessary, it is appreciated that contacts 525 are optional. Figures 5A and 5B also illustrate generally optical waveguide 109 included in semiconductor material 103 and routed through photonic crystal lattice 105. Optical beam 111 is also shown in Figures 5A and 5B being directed through optical waveguide 109 through photonic crystal lattice 105 and semiconductor material 103 in accordance with the teachings of the present invention. In the illustrated embodiment, optical waveguide 109 is shown as a strip waveguide. It is appreciated that in other embodiments, optical

waveguide 109 may be another type of waveguide such as for example a rib waveguide in accordance with the teachings of the present invention.

In one embodiment, each of the plurality of holes 107 is filled with a material having relatively high contrast to semiconductor material 103 and/or second semiconductor material regions 419. For example, in one embodiment, semiconductor material 103 includes crystal silicon and second semiconductor material regions 419 include polysilicon. In one embodiment, crystal silicon and polysilicon have indexes of refraction of approximately 3.45. In one embodiment, each of the plurality of holes 107 is filled with air, which has an index of refraction of approximately 1.0. These example materials are provided for explanation purposes and other suitable materials may be employed in accordance with the teachings of the present invention.

Figure 6A illustrates an example embodiment in which signal 113 is a voltage signal. In particular, signal 113 is shown in the depicted embodiment as a voltage signal V_S, which is applied between contacts 421 and 525 and contacts 423 and 525 in the illustrated embodiment. Accordingly, signal 113 is applied as a voltage through contacts 421 and 423 to second semiconductor regions 419 relative to semiconductor material 103.

Figure 6B illustrates an example embodiment in which signal 113 is a current signal. In particular, signal 113 is shown in the depicted embodiment as a current signal I_S, which is injected through contacts 421

and 423 in the illustrated embodiment. Accordingly, signal 113 may be injected as a current through second semiconductor regions 419 between contacts 421 and 423 to inject charge into second semiconductor regions 419.

Figure 6C is a diagram illustrating generally in greater detail one of the plurality of holes 107 defined in semiconductor material 103 with charge modulated regions 627 formed in response to signal 113 in accordance with the teachings of the present invention. It is appreciated that charge modulated regions 627 are therefore included in the capacitive structures that result from semiconductor material 103 being insulated from second semiconductor material regions 419 with insulating region 317. In particular, Figure 6C shows second semiconductor material region 419 proximate to and insulated from the inside surface of hole 107 defined in semiconductor material 103. Insulating region 317 is disposed between semiconductor material 103 and second semiconductor material region 419 to insulate semiconductor material 103 from second semiconductor material region 419. With signal 113 applied, the charge concentration in charge modulated regions 627 is modulated. As shown in the embodiment depicted in Figure 6C, charge modulated regions 627 includes free charge carriers in semiconductor material 103 and second semiconductor material region 419 proximate to the insulating region 317 proximate to the inside surface of hole 107. In one embodiment, the free charge carriers in charge

modulated regions 627may include for example electrons, holes or a combination thereof.

For explanation purposes, an embodiment in which signal 113 is "low," the concentration of free charge carriers in charge modulated regions 627 is relatively low. Continuing with the example, when signal 113 is "high," the concentration of free charge carriers in charge modulated regions 627 is relatively high. Thus, the signal 113 changes the free charge carrier density in charge modulated regions 627, which results in a change in the refractive index of the semiconductor material in which charge modulated regions 627 are located proximate to the plurality of holes 107. By changing the index of refraction, the effective hole radius is modulated in response to signal 113 in accordance with the teachings of the present invention. By changing the effective hole radius, the photonic band gap of photonic crystal lattice 105 is modulated accordingly, which changes the wavelength of optical beam 111 that is blocked by photonic crystal lattice 105 in accordance with the teachings of the present invention.

In one embodiment, the index of refraction of the semiconductor material in which charge modulated regions 627 is modulated due to the plasma optical effect. The plasma optical effect arises due to an interaction between the optical electric field vector and free charge carriers that may be present along the optical path of an optical beam, such as optical beam 111 in optical waveguide 109. The electric field of the optical beam 111 polarizes the free charge carriers and this effectively perturbs the local dielectric

constant of the medium. This in turn leads to a perturbation of the propagation velocity of the optical wave and hence the index of refraction for the light, since the index of refraction is simply the ratio of the speed of the light in vacuum to that in the medium. Therefore, the index of refraction in optical waveguide 109 proximate to the plurality of holes 107 in photonic crystal lattice 105 is modulated in response to the modulation of free charge carriers in charge modulated regions 627. The modulated index of refraction in the optical waveguide 109 through photonic crystal lattice 105 correspondingly modulates the phase of optical beam 111 propagating through photonic crystal lattice 105. In addition, the free charge carriers in charge modulated regions 627 are accelerated by the field and lead to absorption of the optical field as optical energy is used up. Generally the refractive index perturbation is a complex number with the real part being that part which causes the velocity change and the imaginary part being related to the free charge carrier absorption. In the case of the plasma optical effect in silicon, the refractive index change Δn due to the electron (ΔN_e) and hole (ΔN_h) concentration change is given by:

$$\Delta n = -\frac{e^2\lambda^2}{8\pi^2 c^2 \varepsilon_0 n_0}\left(\frac{b_e(\Delta N_e)^{1.05}}{m_e^*} + \frac{b_h(\Delta N_h)^{0.8}}{m_h^*}\right) \qquad \text{(Equation 1)}$$

where n_o is the nominal index of refraction for silicon, e is the electronic charge, c is the speed of light, ε_0 is the permittivity of free space, m_e^* and m_h^* are the electron and hole effective masses, respectively, b_e and b_h are fitting parameters.

Referring back to the example illustration of Figure 6C, a 6 volt charge may be applied with signal 113 between semiconductor material 103 and second semiconductor material region 419 across insulating region 317, which in one embodiment is approximately 120 Angstroms thick. With the 6 volt applied voltage, the free charge carrier concentration is increased in charge modulated regions 627, which results in a change in the index of refraction of approximately 0.01 of the semiconductor material proximate to hole 107 in accordance with the teachings of the present invention. This refractive index change occurs over approximately 10 nanometers, which results in a 10 percent change in the effective hole diameter of hole 107. As a result, the photonic band gap of the photonic crystal lattice 105 is modulated in accordance with the teachings or the present invention.

With reference now to the embodiments shown in Figures 7A and 7B, optical beam 111 is illustrated being directed through optical waveguide 109 through semiconductor material 103 through photonic crystal lattice 105. In the illustrated embodiment, optical beam 111 includes two wavelengths λ1 and λ2 before being directed through photonic crystal lattice. In one embodiment, wavelengths λ1 and λ2 are infrared wavelengths near for example approximately 1310 nanometers or 1550 nanometers or the like. In Figure 7A, signal 113 is illustrated to be a "low" voltage signal V_S. In the illustrated embodiment, with signal V_S "low," photonic band gap of the photonic crystal lattice 105 blocks the wavelength λ2 of optical beam 111, but allows the other wavelengths of the optical beam 111, such as λ1, to

propagate through photonic crystal lattice 105. In Figure 7B, signal 113 is now illustrated to be a "high" voltage signal V_S. With signal V_S "high," photonic band gap of the photonic crystal lattice 105 is now modulated to block the wavelength λ1 of optical beam 111, but the other wavelengths of the optical beam 111, such as λ2, are now allowed to propagate through photonic crystal lattice 105.

Figure 8 is a diagram illustrating generally one embodiment of a system including an optical transmitter, an optical receiver and an optical device including a photonic crystal lattice to modulate or switch an optical beam in accordance with the teachings of the present invention. In particular, Figure 8 shows optical system 833 including an optical transmitter 829 and an optical receiver 831 with an optical device 101 optically coupled between optical transmitter 829 and optical receiver 831. As shown in Figure 8, optical transmitter 829 transmits an optical beam 111 that is received by optical device 101.

In one embodiment, optical device 101 includes a device such as one of the embodiments of the optical devices described previously to modulate or switch optical beam 111 or a specific wavelength of optical beam 111 in response to signal 113. For example, if optical beam 111 transmitted from optical transmitter 829 includes a wavelength λ, optical device 101 receives optical beam 111 and may be used to modulate the wavelength λ of optical 111 to encode signal 113 onto optical beam 111 according to an embodiment of the present invention. Optical beam 111 is then directed

from optical device 101 and received by optical receiver 831 with signal 113 encoded on optical beam 111.

In another embodiment, optical beam 111 transmitted from optical transmitter 829 may have a plurality of wavelengths including for example λ1 and λ2. Optical device 113 may be used to selectively block or filter out one of the wavelengths λ1 or λ2 while allowing the other wavelengths to propagate through in response to signal 113. Any remaining wavelengths included in optical beam 111 are then directed from optical device 101 to optical receiver 831. In other embodiments, it is appreciated that a plurality of optical devices 101 may be utilized as building blocks and be arranged or cascaded in various configurations to operate on a variety of wavelengths that may be included in optical beam 111 according to embodiments of the present invention.

In the foregoing detailed description, the method and apparatus of the present invention have been described with reference to specific exemplary embodiments thereof. It will, however, be evident that various modifications and changes may be made thereto without departing from the broader spirit and scope of the present invention. The present specification and figures are accordingly to be regarded as illustrative rather than restrictive.